FORESTRY ENERGY AGREEMENT
INTERNATIONAL ENERGY AGENCY

PROGRAMME GROUPE B –
BIOMASS GROWTH AND PRODUCTION

Environment Canada Environnement Canada

Biomass Qualities for Energy Conversion with Particular Reference to the Combustion of Wood

M. Neenan
Ireland

ONTARIO TREE IMPROVEMENT AND FOREST
BIOMASS INSTITUTE
MINISTRY OF NATURAL RESOURCES
MAPLE, ONTARIO, CANADA

ERRATUM 85-0705/

Page 2, Paragraph 3, Line 1

9,500 cal/gram

should read

6,500 cal/gram

BIOMASS QUALITIES FOR ENERGY CONVERSION WITH PARTICULAR REFERENCE TO THE COMBUSTION OF WOOD

by

M. Heenan
Agricultural Institute
Oak Park Research Centre
Carlow, Ireland

Report No. 2, 1984

Programme Group 'B' -
Biomass Growth and Production
International Energy Agency
Forestry Energy Agreement

This report was prepared for JAB 31 and has been reviewed by:

J. Balatinecz, Canada
P. Lunny, Ireland

Edited by: D. Morgan and L. Zsuffa, Canada

The IEA/FE - Biomass Growth and Production Program is assisted by the Faculty of Forestry, University of Toronto.

PREFACE

In April, 1978, a number of countries within the International Energy Agency (IEA) decided to sign an Implementing Agreement (IA) for a program of research, development and demonstration on forestry energy. The work is implemented via Programme Groups and Cooperative Projects.

Work within the group for biomass growth and production has resulted in several reports which are being published in this series. The funds for the publication of these reports have been supplied by the International Energy Agency's Forestry Energy Agreement, the National Research Council of Canada and the Canadian Forestry Service.

L. Zsuffa
Chairman
Programme Group 'B'

Keenan, M. Biomass qualities for energy conversion with particular reference to the combustion of wood. IEA/FE PG'B', Report 1984:2. 19 pp. + appendix.

ABSTRACT

Although fuelwood is widely available in many countries, a survey shows that at present this wood is not being widely used. The reasons for this are technical and institutional as well as social. The lack of use is particularly noticeable in the industrial sector. One reason may be that wood fuel is not as yet an important item of commerce for fuel or chemical processing. This in turn is due to the presumption that wood is extremely variable in calorific value and moisture content. However, calorific values vary within a relatively narrow range as compared to coal. The moisture content of freshly-cut wood varies within the range of 35.0 to 50.0% over the year but is much narrower if it is harvested during the dormant months. Th use of wood fuel could possibly be extended if better information was available on drying and storage. Pilot demonstration projects are necessary to overcome the psychological and institutional barriers which operate against any new energy source.

CONTENTS

	Page
Introduction	1
Chemical Composition of Wood	1
Major Constituents	1
Minor Constituents	3
Volatile Constituents	3
Ash Content	4
Moisture Content	4
Forms of Moisture	4
Moisture Content of Plant Parts	5
Seasonal Variation in Moisture Content	5
Bulk and Density of Wood Fuel	6
Specific Gravity	6
Bulk/Weight Ratios of Wood Products	6
Energy Intensity	8
Variations in the Calorific Value of Wood Fuel	8
Variations in Calorific Value Due to Plant Components	8
Variations in Calorific Value Between Clones	9
The Principles of Combustion of Wood	10
Stoking Problems	10
Air Supply	10
Particle Size and Shape	11
Effect of Moisture Content	11
Environmental and Institutional Problems	13
Institutional Factors	13
Present and Future Situation	14
Discussion	14
Acknowledgements	16
Bibliography	17
Appendix 1 - Questionnaire Results	1

INTRODUCTION

Biomass is expected to supply 5.0 to 10.0% of all energy by 1990. Energy use is usually divided into four categories, namely: domestic, process heat, electricity and transportation. Wood has the potential for supplying a proportion of the first three which comprise about 75.0% of energy use in most countries (Anon., 1979). Forms of biomass other than wood may be more suitable for supplying transportation fuels.

The conversion processes for woody materials have been reviewed in a retrospective search of the International Energy Agency's (IEA) Information Service. A number of demonstration projects on methyl alcohol production and gasification are already in progress in Europe and North America. However, the more immediate use of wood is likely to be direct combustion.

The two main types of wood envisaged for energy use are forest thinnings and residues, and trees from specially-grown plantations. The availability of forest thinnings, tops and branches, and residues from conventional forestry is well documented for most countries. Plantations may be grown as three to four year coppice, or eight to twelve year single stems at reduced spacing. This short-rotation forestry can produce fuel at a price which is competitive with oil and coal.

Although research on both types of woody biomass is reaching a stage where it could be applied in practice, indications are that wood fuel is not being used as widely as might have been expected.

Durand (1980) examined possible causes inhibiting the use of solar energy. Amongst the most important of these are doubts concerning return on investment, ambiguous attitudes of public utilities, ignorance of consumer protection measures, regulatory measures, and "psychological obstacles caused by exaggerated expectations combined with a mistrust of immediate feasibility". These are also true for all new sources of energy, including energy from biomass.

This overview, which is by no means exhaustive, attempts to examine the major issues involved in the use of biomass for energy conversion.

As the literature on the subject extends over a wide range, it is only possible to refer briefly to one or two papers in each section. Because of large differences which can occur in one species over a range of latitudes (Somerby, 1979), no attempt was made at a critical comparison between the results obtained by different workers.

CHEMICAL COMPOSITION OF WOOD

Major Constituents

Stem wood contains approximately 50.0% carbon, 42.0% oxygen, 6.0% hydrogen and 1.0% ash. Bark is similar to stem wood except that it contains about 4.0% less oxygen and somewhat over 4.0% more ash (Koch, 1972) (Table 1).

Table 1: Chemical Composition and Typical Heating Values of Wood, Coal and Peat.

	Hardwood			
	Wood	Bark	Coal	Peat
Hydrogen	6.4	6.0	5.0-6.4	6.0
Carbon	50.8	51.2	55.0-74.0	51-59
Oxygen	41.8	37.9	7.0-34.0	31-40
Sulphur	---	---	0.4-2.1	---
Nitrogen	0.4	0.4	1.0-1.5	0.81
Ash	0.9	5.2	3.3-10.1	1.8-8.0
Heating value Btu/lb	7827	7593	9420-13310	6000-7000
K cal kg^{-1}	4348	4220	5222-7388	3330-5300

(from: Hall and Arola In Karchesy and Koch, 1979)

The air requirement for combustion varies with the chemical composition of the fuel according to the following equation:

$$Ma = 11.5\ C + 34.4\ H$$

where Ma is the number of kg of air required to burn 1.0 kg of fuel, and C and H are the weights of carbon and hydrogen in 1.0 kg of fuel.

The ratio of carbon to oxygen is quite different for coal and wood. This means there is a greater potential for chemical reactions to occur in the burning of wood. Moreover, wood contains ring structures whereas coal is amorphous carbon. This can create problems due to the occurrence of poly-aromatic hydrocarbons in the smoke. This is further discussed below.

Lignin has a calorific value of about 9,500 cal/gram as compared to 4,230 cal/gram for cellulose. The proportions of the main polymers vary somewhat between species. (Table 2). Similar values from other authors are quoted by Harker et al. (1982), Tillinan (1978) and Browning (1963).

Lignin content increases with age in poplar (Stevens, 1982). Some unpublished Canadian work has given a range in lignin content of 19.0 to 23.5% for three-year-old poplar sprouts and from 26.0 to 35.0% for willows (Anderson, 1981, pers. comm.). Leaves of poplar can also show variation in their content of phenolic compounds (Anderson and Bowman, 1979). This diversity in chemical composition could be expected to cause some slight, but not by any means large, variations in the fuel value of wood fuel.

Table 2: Proportions (%) of Different Polymers in Wood as Given by Different Sources

	Harcheey & Koch (1979) Hardwoods	Martin & Francis (1954) Hardwoods	Martin & Francis (1954) Conifers	Koch (1972) Pine
Holocellulose	67.0-86.0	51.7-71.4	60.6-64.8	65.0-71.0
Lignin	19.0-30.0	23.7-44.5	30.6-32.0	26.0-30.0
Resins and Waxes		0.46-1.55	1.10-1.85	2.0-3.0
Water soluble substances	1.1-9.6	3.27-6.20	1.43-4.60	3.0-9.0

Minor Constituents

The minor constituents of wood, known as "extractives" constitute 1.1 to 9.0% of hardwoods in the United States. It has been suggested that the extractives and lignins may account for seasonal variations which occur in the calorific value of wood (Howard, 1973).

A high content of extractives may indicate an abundance of soluble carbohydrates and, therefore, a greater risk of microbial decomposition or heating in storage.

Volatile Constituents

The proportion of volatile constituents in any fuel is highly important. Maximum utilization of these substances is necessary if efficient combustion is to be attained. Also, unburned volatiles are a source of pollution to the atmosphere. If wood with a high moisture content is heated at low temperatures, some of the volatile constituents become distilled and are deposited as tar, which creates a fire hazard. Specific studies on tar emission have not been made for the production of woodfuel, but information from the wood distillation industry gives some indication of the problems involved (Table 3).

The chemical composition of the distillate varies with the temperature (Martin and Francis, 1954). Up to 150°C, it consists mainly of water but between 150°C and 280°C, most of the acetic acid and methyl alcohol is distilled. From 225°C up to 350°C tar is produced with a peak in production occurring at about 300°C. Tar, which is a complex mixture of parafins, other hydrocarbons, phenols, esters and fatty acids, is highly inflammable.

Table 3: Effect of Rate of Heating on Yield of Tar From Different Species

	Tar as a % of dry matter
Beech slowly heated	5.9
Beech quickly heated	4.9
Oak slowly heated	3.7
Oak quickly heated	3.2
Birch slowly heated	5.5
Birch quickly heated	3.2
Pine slowly heated	4.4
Pine quickly heated	9.8

(from: Martin and Francis, 1954)

Ash Content

Wood contains 0.5 to 1.0% and bark may contain up to 9.0% ash. The overall ash content will therefore vary with the diameter of the wood; wood grown on short-rotations should contain more mineral matter than mature wood. In older wood, ash consists largely of calcium and silica and hence has a low fertilizing value.

A high ash content is undesireable in that it creates a disposal problem, but a small percentage of ash is useful in protecting the bars of the grate from oxidation during combustion. According to Olkinoura (1982), normal 3 mm steel which is satisfactory for log fuel, can become corroded by wood acids in one year if chips, i.e. mature wood, are used. The difference may be due to the respective ash contents.

MOISTURE CONTENT

Forms of Moisture

Moisture content has a critical effect on the efficiency of burning. Water in wood occurs in three forms: as vapour and free water in the lumens, and as bound water. The latter is associated with the cell walls by a number of different processes (Koch, 1972). When all the water in the lumens has been removed, the fibre saturation point occurs (approximately 30.0% moisture content). Wood in contact with air reaches an equilibrium moisture content which depends on the relative humidity and temperature. Tables are available showing the equilibrium moisture content for different temperatures and relative humidities for log wood (Koch, 1972). At a relative humidity of 90.0% and a temperature of 25°C, the equilibrium moisture is approximately 20.0%. Equilibrium moisture at close to zero temperatures has not been extensively researched but Schmidt, quoted by Koch (1972), found that in sitka spruce and Douglas fir, at -21°C and 90.0% relative humidity, fibre saturation occurred at

about 21.0% moisture. It would seem, therefore, that a moisture content of 30% can easily be achieved from air drying, and that a moisture equilibrium content of about 20.0% could be maintained even at sub-zero temperatures.

Moisture Content of Plant Parts

Variations in moisture content occur between plant components in wood from both forest residues and short-rotation forestry. The moisture content of mature pine components is shown in Table 4.

Table 4: Variations in Moisture Content of Portions of Pine Trees Seven to Twenty-One Years Old

Tree portion	% moisture (wet basis)
Upper one third of crown	60.2
Mid one third of crown	59.8
Lower one third of crown	59.1
Below crown	56.7
Dead branches	32.8

(from: Koch, 1972)

Sennerby (1979) found that the moisture in short-rotation wood of *Salix* spp. decreased from the stump to the shoot tip. On a wet weight basis this ranged from 50.0 to 41.2% for *Salix caprea* and 54.5 to 42.2% for *S. pentandra*. When samples were taken at 1.3 m from the ground, moisture content varied by a factor of just over 2.0. Some differences occurred due to geographical location of the sites. This may be a reflection of the pattern of the growing season in different areas.

Seasonal Variation in Moisture Content

Wood from short-rotation plantations has a higher overall, and a greater seasonal fluctuation in, moisture content than mature wood. Nilsson (1982) found a statistically useful relationship between dry matter content and stool size in *Salix*. The moisture content of three species, *Salix viminalis* x *purpurea* 077, *S. smithiana* 666 and *S. viminalis* 683, was lowest in November at 40.0 to 50.0% on a wet weight basis.

Seasonal variation in moisture content also occurs in mature trees from conventional forests. Cores taken in mid-winter had higher moisture contents than cores taken in summer (Choong and Fog, 1970). Sennerby (1979) found that the moisture content of *Betula* was highest in May to June, and lowest in September to October. Anderson (1979) reported that

the ratio of dry weight to wet weight in the stemwood of poplar varied from 0.327 in July to 0.494 in September. The ratio in unlignified tissue varied from 0.198 to 0.422. Similar variations have been found by Keenan (1982) for whole, immature trees of Alnus and Salix coppice sampled at monthly intervals. The large seasonal differences which occur are presumably related to the proportion of immature or unlignified shoots present.

The most important conclusion to emerge is perhaps that the moisture content of wood can be substantially below 50.0% on a wet-weight basis. Short-rotation wood is no worse than forest thinnings in this respect. A moisture content of 30.0% can be obtained, and maintained, under ambient air conditions. These latter moisture contents are satisfactory from the point of view of the combustion engineer, whereas wood containing 60% moisture, such as in freshly harvested conifers, is highly unsatisfactory in this respect.

BULK AND DENSITY OF WOOD FUEL

Transportation, handling and storage costs are important economic factors in the feasibility of wood fuel use. These can be viewed from a number of different respects.

Specific Gravity

Density on the basis of wet volume and dry weight provides an important link between the forester's measurement in the field and the combustion engineer's requirement at the boiler. Equations connecting the two are of particular importance. Sennerby (1979) reported values in the range of 350.0 to 550.0 kg/m^3 for Salix pentendra, and with one exception, from 450.0 to 525.0 kg/m^3 for S. caprea.

Flower-Ellis & Olson (1981) reviewed the literature and found differences in wood density and bark content of different clones of twenty-one Salix clones grown in Sweden. Wood density increased linearly with diameter. The range in density was 266.0 to 397.0 kg/m^3.

In a study on young poplar, Stevens (1982) found density values which ranged from 0.310 to 0.510. Steenackers and van Slycken (1980), determined the density of juvenile wood in 171 clones, and found this parameter to be fairly consistent in two successive years. They concluded that it is possible to use this as a selection criterion in breeding.

Bulk/Weight Ratios of Wood Products

The volume-weight ratio has an important bearing on the transportation cost of the biomass. Low-grade material may not justify the cost of transportation over any appreciable distance. There is already much information on transport and handling costs for wood chips; this is probably also applicable to chips from wood grown on short-rotations. Some typical results are given in Table 5.

Table 5: Effect of Bulk/Weight Relationship on Cost of Fuel from Woody Waste

Fuel Type	Moisture % (dry wt.)	Weight per unit lb/c.ft	kg/m^3	Available energy fresh wt. basis Btu/ton	GJ/tonne	Cost ($U.S.) of transportation Btu/ton	GJ/km
Bark	40.0	21.0	336.0	12.3	11.77	0.762	0.45
Sawdust	80.0	15.0	240.0	9.6	9.19	1.283	0.75
Shavings	15.0	13.0	208.0	15.0	14.35	0.884	0.52
Whole tree chips	100.0	32.0	513.0	8.6	8.23	1.220	0.72
Pulp chips	90.0	21.0	336.0	9.0	8.61	1.142	0.67

(from: Ames et al., 1982)

The storage factor (cubic feet per long ton) is given as 60 to 110 as against about 20 for most ores (Anon., 1976). Containers are designed for a factor of 45 to 60. The fluffing factor (total volume/volume of solid wood) is 2.3 to 2.8. Settling during transport by truck is in the range of 4.0 to 10.0% over a distance of 100.0 km, but most of this occurs during the first 20.0 to 40.0 km. All of these factors are affected by chip size, distribution, and the amount of sawdust present (Anon., 1976).

In the case of roundwood and logwood, there is much less published information on bulk and transportation problems. Marsinko & Wooten (1982) have provided data for small trucks which can be extended with slight modifications to larger containers. The critical statistics are given in Table 6. From this type of information, it is possible to formulate accurate costings of the procurement of fuel in the form of thinnings.

Table 6: Variations in the Cubic Capacity of Trucks According to the Method of Loading and Length of Logs

Volume of truck	Length or diameter	Method of loading	Volume of wood carried cu.ft.	(cu.m)
48.5 (1.37)	1.5 ft logs (0.45 m)	Random	29.8	(0.84)
		Stacked	40.8	(1.16)
48.5 (1.37)	2.0 ft logs (0.60 m)	Random	29.8	(0.84)
		Stacked	39.3	(1.10)

(from: Marsinko and Wooten, 1982)

Blankenhorn et al. (1982) have introduced an interesting principle for costing the transportation of wood chips. This assumes that a certain fraction of the wood is consumed in the transportation process, so that it has a much lower net energy value when delivered at the furnace. This method has the great advantage that costs can be used on an international basis independently of changes in currency.

The usable energy in wood is assumed to be 16.4 MJ/kg. Running costs for transportation are 1.0 MJ/t/km, and chipping consumes 84.3 MJ/t dry matter. The capital energy of the tractor and other equipment (159.0 and 121.0 MJ/kg respectively) is discounted over the lifetime of these machines. Assuming a life of 16,000 hours, the cost of harvesting, chipping and haulage to the loading point is 0.7272 MJ/t. Therefore, the energy cost of transportation including capital energy is 0.0804 MJ/kg of green wood for a haulage distance of 50.0 km.

Energy Intensity

One of the main disadvantages of woodfuel is its low mass energy density (MED) or volume energy density (VED). This is illustrated in Table 7 from Reed & Bryant (1978) quoted by Balatinecz (1982).

Table 7: Energy Densities of Different Fuels by Mass and Volume

Fuel	Moisture Content	Density	Heat of Combustion MED (kJ/g)	Heat of Combustion VED ($kJ.cm^3$)
Biomass	50	1.0	9.2	9.2
	10	0.6	18.6	11.2
Densified biomass	10	1.0	18.6	20.9
	10	1.25	18.6	26.1
Coal (bituminous)	0	1.3	28.0	36.4

(from: Reed and Bryant In Balatinecz, 1982)

Such differences necessitate a larger storage area and greater handling costs than in the case of coal. These problems can be overcome by densification of the wood, or by the use of larger boilers. However, this characteristic of woodfuel may explain some of the institutional factors inhibiting its use.

VARIATIONS IN THE CALORIFIC VALUE OF WOOD FUEL

Variations in Calorific Value Due to Plant Components

Harker et al. (1982) have recently summarized the results of all published work on calorific values of wood. Karchesy & Koch (1979) have recorded the values for wood and bark of twenty-three species of hardwoods

in the United States. These vary within the relatively narrow range of 18,000 to 21,000 KJ/kg of wood. Differences between plant components tend to be greater than between species. Table 8 from Keenan & Steinbeck (1979) illustrates this point. Differences between species were statistically significant but of a very small magnitude.

Table 8: Calorific Values of Nine Species of Hardwoods Collected in Midsummer (oven-dry weight basis)

Species	Wood	Bark	Branches	Twigs	Leaves
	KJ/grm				
Green ash	19.96	19.33	20.34	20.17	21.43
Black Cherry	19.95	20.72	20.27	20.37	21.91
Boxelder	20.49	18.09	20.44	20.26	21.05
Redbud	20.36	19.39	19.84	19.83	21.30
Red Maple	20.13	19.08	19.93	19.97	20.83
Sweetgum	19.77	19.13	19.61	19.69	19.50
Sycamore	19.91	20.00	20.33	20.40	21.65
Water oak	20.00	19.35	19.91	20.17	21.29
Yellow poplar	20.18	19.39	20.09	20.02	21.21
Mean	20.00	19.39	20.08	20.10	21.13

(from: Keenan and Steinbeck, 1979)

Variations in Calorific Value Between Clones

Sastry & Anderson (1980) found small but significant differences in calorific value between clones of poplar. Clones of the Aigeiros group were significantly better than those of the Leuce group. Differences did not correlate well with specific gravity, but there seemed to be an association with extractives. The results are given in Table 9. Differences between clones, although significant, are small as compared with differences in yield of wood.

Table 9: Calorific Values and Specific Gravities of Two-Year-Old Hybrid Poplar Clones

Clone		Mean calorific value (KJ/grm)	Specific gravity
D72	P. deltoides	20.75	0.390
DTac1	P. deltoides x berolinensis	20.14	0.408
DN87	P. nigra	20.05	0.404
I45/15	P. x euramericana	20.02	0.370
DN10	P. x euramericana cv. Robusta	19.56	0.447
AGC11	(P. alba x grandidentata x P. canescens	19.49	0.427
GA88	P. grandidentata	19.42	0.371
A-499	(P. alba)	19.18	0.333
GAC131	P. canescens x (P. alba x P. grandidentata)	18.60	0.402
AK-14	(P. alba x davidiana)	18.24	0.413

(from: Sastry and Anderson, 1980)

THE PRINCIPLES OF COMBUSTION OF WOOD

There are fewer differences in calorific value between species of trees than between different grades of coal. For the purpose of this discussion the approximate analysis of wood is assumed to be:

Fixed carbon	-	20.0%
Volatiles	-	79.0%
Ash	-	1.0%

In grate systems (which include all domestic stoves as well as large, industrial, solid-fuel appliances) the fixed carbon burns on the grate as incandescent charcoal, an almost ideal solid fuel which presents few or no combustion problems. The volatiles form flames and hot gases. The control of volatile combustion presents the greatest problem. Since about two-thirds of the energy in wood resides in the volatiles, the importance of such control is quite obvious.

Stoking Problems

When fresh wood is introduced to a furnace, the emission of volatiles depends only on the furnace temperature and is not amenable to external control. The addition of large increments of fuel results in correspondingly heavy volatile emission. If the air supply is sufficient, these constituents can, of course, be burned (and must be if atmospheric pollution is to be avoided). However, if the amount of heat from the volatiles is large, this may be more than the heat transfer surfaces can utilize; the temperature of the waste gases may be excessive, reducing furnace efficiency.

Volatile emission can be controlled only by controlling the fuel feed, and ideally this can be done by adding the fuel continuously at a rate matched to the air supply and the heat demand. A continuous feed can be achieved either mechanically or, for a domestic heating stove, manually in as small increments as possible.

The use of refractory furnaces permits the addition of larger increments at less frequent intervals. The refractory material absorbs the heat released by sudden emission of volatiles, releasing it again between fuelings. In short, it acts as a thermal flywheel. The arrangement is inherently inflexible, but has been used in external Dutch-oven furnaces and in large domestic stoves.

The volatiles should be burned completely and at the highest possible temperature. The rate of radiant heat transfer from a flame to the transfer surface, is proportional to the fourth power of the absolute temperature. Raising the flame temperature from 1200°C to 1500°C, for instance, will more than double radiant heat transfer rates, and make it possible to reduce the heat transfer surfaces by more than half. This will obviously greatly affect the capital cost of the plant.

Air Supply

The supply of sufficient air (preferably preheated) for complete combustion, and rapid mixing of this air with the rising volatiles, is necessary to achieve the desired effect. The higher the degree of

turbulence, the more effective will be the mixing. Turbulence may be achieved by supplying combustion air at high velocity, e.g. by reducing the grate area. This achieves quicker burn-out and, therefore, more intense combustion.

If the combustion air velocity is increased beyond a certain point, the fire will start to lift off the grate. Before this happens small particles will become entrained and possibly be carried out of the furnace incompletely burned. Fluidization will begin to occur at an air speed of about one metre per second, at which speed small particles will begin to leave the bed. At this speed, and assuming stoichiometric conditions, the heat release would be about 120.0 GJ/m^2 grate area/hr. At 50.0% excess air, and an air speed of 1.0 m/sec., the heat release would be approximately 8.0 GJ/m^2/hr. This would correspond to a burning rate of 430.0 kg of dry matter, or about 640.0 kg of air dried wood/m^2/hr. Rates higher than this are common in American wood-burning boilers. These are usually fired by spreader stokers, and a high proportion of the fuel (the lighter constituents) is burned in suspension and not on the grate.

Particle Size and Shape

The foregoing considerations highlight the importance of particle size and shape. With conventional pulpwood chips, the 'terminal settling velocity' corresponding to the air speed which will hold them in suspension is 3.0 to 4.9 m/sec. With bone dry and partially carbonized chips, the terminal settling velocity will be substantially less. Gas speeds in certain parts of a furnace are frequently in excess of the figures mentioned above, so the use of pulpwood sized chips in a modern boiler will inevitably lead to carryover of partially burned, or burning, chips out of the furnace area. Fuel particles should be heavy enough to remain on the grate. There is, however, an upper limit. To ensure that combustion air will react with the fuel, the firebed depth should not be less than three times the average particle diameter. If the firebed is more than six times the average particle diameter size, the oxygen will be consumed before it reaches the surface of the bed, and 'black top' conditions will prevail. Therefore, the ideal particle diameter will be determined by the acceptable firebed depth and this is dictated by furnace and stoker dimensions. In practice, the particle diameter should vary, from perhaps 12.0 mm (small boilers) to 100.0 mm (large plants).

These remarks apply to industrial and semi-industrial plants, which work under forced and induced draught. With hand-fed domestic appliances, air speeds and combustion rates are much smaller and different considerations apply.

Effect of Moisture Content

At about 89% moisture content there is just sufficient energy in the dry matter to evaporate the associated moisture (i.e. 89.0% moisture corresponds to zero net calorific value). This is, of course, a purely theoretical figure. The dry matter could not burn completely unless there was enough energy in it, not only to evaporate the moisture but to raise its volatile constituents to their ignition temperature (about 700°C). Before this happens, the moisture content has to be lowered to about 69.0%, otherwise the furnace will black out. Progressively lowering the

moisture content will raise the flame temperature over the figure of 700°C, and at a moisture content of 30.0%, the theoretical flame temperature will be in the region of 1450°C, assuming stoichiometric conditions. The influence of flame temperature on the capital cost of boilers has been referred to above.

Apart from the effect of moisture content on flame temperatures, there is the obvious effect on heat losses. The moisture not only has to be evaporated but also superheated to the exhaust temperature. If the exhaust temperature, for instance, is 200°C then the loss of energy due to superheating represents about 340.0 MJ/kg water evaporated (this is over and above the 2,570 MJ required to evaporate the water). Since the amount of dry matter present decreases as the moisture content increases, the percentage of heat used up in evaporation and superheating increases rapidly with increasing moisture content. Table 10 illustrates this effectively.

Table 10: Effect of Moisture Content on Net Calorific Value of Wood*

Dry weight of wood kg	Water in wood kg	Moisture content of wood wet basis %	Heat required to evaporate water in wood MJ	Heat required to evaporate water from hydrogen in wood MJ	Net calorific value MJ/kg
1	7.24	86.19	18,612	1,388	0
1	4.00	80.00	10,280	1,388	8,322
1	2.33	70.00	2,988	1,388	12,624
1	1.50	60.00	3,855	1,388	14,757
1	1.00	50.00	2,570	1,388	16,042
1	0.67	40.00	1,722	1,388	16,890
1	0.43	30.00	1,105	1,388	17,507
1	0.25	20.00	642	1,388	17,970
1	0.11	10.00	283	1,388	18,329
1	0.00	0.00	0	1,388	18,612

*assumed: dry wood has a gross calorific value of 20.0 MJ/kg and contains 6% hydrogen

(from: Barker et al., 1982)

These considerations all point to the critical importance of the moisture content of the wood. Air-drying appears to be the best option. Artificial drying necessitates the use of fuel, and while the process would be more efficient than drying in the furnace (as happens when wet wood is fed directly into the furnace) it is unlikely that the saving would justify the capital cost of a drying plant.

A boiler designed to burn coal will not necessarily be satisfactory for wood. A positive decision regarding furnace type needs to be made if long-term use of wood is intended; moreover, a particular kind of wood i.e. roundwood, chips or briquettes must be assumed.

There are, of course, other methods of burning timber besides grate-firing. These are pulverized fuel, suspension and semi-suspension firing, and fluidized bed combustion. The high volatile content of wood indicates that it would be highly suitable for pulverized fuel or suspension firing. Appliances based on these principles are now being developed commercially in many countries. A comprehensive study of the problems of burning wood in industrial boilers has been provided by Karchesy and Koch (1979).

ENVIRONMENTAL AND INSTITUTIONAL PROBLEMS

The environmental impact of any new technology must be taken into account, and be overcome as far as possible.

Wood smoke is almost free of sulphur, which gives it an advantage over coal from an environmental point of view. However, it contains poly-aromatic hydrocarbons which are not only irritating to the eyes, but contain substances which are suspected of being carcinogenic (Ramdahl et al., 1981, Rendall et al., 1982, Karcher et al., 1981, and Karcher, 1982). While this is not an insurmountable problem, stoves and boilers must be designed so that risks are minimal. This may result in further costs.

There are a number of problems associated with storage. Wood chips are more prone than coal to damage by rain because wood contains a high proportion of hemicelluloses which have colloidal properties and, therefore, hold water. This is important in some climates. In addition, because of the presence of a small proportion of sugars, wood is susceptible to microbial decomposition in storage. This problem has been studied extensively by Gisleröd (1982) who found that the most common species present were Penicillium, Cladosporium, Aspergillus and Trichoderma. Spores from such fungi can cause the respiratory disease known as 'farmers lung'. The problem is not, however, a major one in the use of wood fuel.

Institutional Factors

As stated by Durand (1980), the use of a new technology may be hindered by institutional and psychological factors. In the case of wood, these may be more important that the purely physical properties of the fuel. The major institutional barrier may be the reluctance to invest in stokers and transport systems suitable for wood. The new investment which may be required for the utilisation of wood may be the critical factor inhibiting the use of wood energy.

The same consideration applies to storage of the fuel. As shown in Table 7, coal has a greater energy intensity on a volume basis than solid wood. This difference is also reflected in the ground storage area; for wood chips about 1.0 m^2 is required per 2.8 m^3 of chips. The lack of sufficient storage space could be a major factor limiting the use of wood chips in built up areas.

The Present and Future Situation

New investments in wood-burning devices will not be forthcoming unless there is more published information, and more pilot demonstrations on wood fuel. The most recent situation with regard to the use of wood as fuel in IEA/FE countries is given in Appendix 1. These results are substantially in agreement with previous studies by other investigators (Zsuffa and Morgan, 1982; Paavilainen and Perm, 1981).

DISCUSSION

If wood is to be used more widely as fuel, certain problems must be overcome. These are partly technical but are mostly institutional. The main arguments against the use of wood are that it is variable in calorific value, it is not always in convenient sizes, its moisture content is too high and its energy content on a weight or volume basis is too low. These are valid objections and must be considered. The coal industry has solved the problem by grading and standardization. In the case of wood fuel, there is both an absence of marketing arrangements (Isachsen, 1982) and a lack of specifications. There may be a substantial market for roundwood or chips provided some purchasing specifications can be established.

Since the elemental composition of wood is remarkably constant, it is not difficult to design installations which burn mature wood, bark and coppice, all with a high degree of efficiency. Already, there are many types available commercially.

The greatest single problem is moisture content. The presence of moisture affects boiler efficiency, boiler investment costs and the presence of tar and other unwanted emissions. This is especially important with regard to freshly harvested wood which usually has a natural moisture content of more than 50.0% on a wet weight basis.

The limited evidence available indicates that increased yield brought about by genetic improvement does not result in a lower dry matter content. On the contrary, there is evidence that volume yield, specific gravity and calorific value can be improved simultaneously (Anderson and Zsuffa, 1981, Steenackers and van Slycken, 1980).

As the content of hemicelluloses in wood from short-rotations is largely unknown, and since direct moisture equilibrium studies have not been undertaken, the problems of deterioration in storage are still unclear. There is, however, no such problem with conifers, which may explain why hog fuel is now more widely used by industry in the United States.

There is a need for extensive and systematic studies on moisture content of large stockpiles and for pilot studies on burning.

Volume and weight energy density can be a problem with regard to transportation costs, storage space and boiler size.

Balatinecz (1982) has listed the disadvantages of raw biomass as a fuel as follows:-

- relatively low heat value per unit volume
- variability of quality and heat value
- difficulty in control of the rate of burning
- rapid burning, necessitating frequent refuelling
- difficulty in mechanizing continuous feeding
- large area requirement for storage
- economic problems in transportation and distribution
- subject to bio-deterioration

These problems can be overcome by densification, but the cost may be too high for Utilities. The experience in Ireland with peat over the past thirty years has shown that the standarised briquette has held its share of the domestic market at a time when hand harvested peat showed a steady decline.

As pointed out by Durand (1980), there are psychological and institutional problems hindering the introduction of any new technology. New investments in wood burning devices will not be forthcoming unless there is more published information, and more pilot demonstration on wood fuel.

ACKNOWLEDGEMENTS

Sincere gratitude is extended to the IEA delegates and observers who provided the information on wood use in different countries. The author is indebted to F. Lunny, consulting engineer, who wrote the section on the principles of wood combustion and who made many corrections to the manuscript.

BIBLIOGRAPHY

Ames, G.C.W., H.O. Baxter and J.V. Harper. 1982. Potential use of wood residues for energy in Georgia. University of Georgia, Research Bulletin 275.

Anderson, H.W. 1979. Biomass production of hybrid poplar grown in minirotation. Proc. N. Amer. Poplar Council Annual Meeting, Brockville, Ontario, September, 1977. Ontario Ministry of Natural Resources.

Anderson, H.W. 1981. Personal communication. May, 1981.

Anderson, H.W. and K. Bowman. 1979. Some aspects of chemotaxonomy of hybrid poplar. In: Poplar research, management and utilization in Canada, Report 13. Ontario Ministry of Natural Resources.

Anderson, H.W. and L. Zsuffa. 1981. Genetically-improved biomass energy production. Ontario Ministry of Natural Resources.

Anon. 1976. Woodchips, production, handling and transport. (2nd ed.) F.A.O. Rome, p. 58-95.

Anon. 1979. Energy policies and programmes of I.E.A. countries. OECD, Paris.

Balatinecz, J. 1982. The potential role of densification in biomass utilization. Presented to NATO Advanced Studies Institute Symposium on Biomass Utilization, Portugal, September 26 - October 8.

Blankenhorn, P.R., T.W. Bowerson and R.E. Meyers. 1982. Energy relationships for selected cultural investments. For. Sci. Vol. 28, No. 3, pp. 459-469.

Browning, B.L. 1963. The chemistry of wood. Interscience Publishers, London.

Choong, E.T. and P.J. Fog. 1970. Forestry Notes 93, (quoted by Koch, 1972) p. 272.

Durand, M. 1980. Non-technical obstacles to the use of solar energy. A. Strub and T.C. Steemers (eds.) Hardwood Academic Publishers.

Flower-Ellis, J.G.K. and L. Olsson. 1981. Wood density and the weight and proportion of bark in current shoots of Salix clones. Projekt Energiskogsodling Institutionen for Ekologi och miljovard. Sveriges Landbruksuniversitat. Tech. Rep. No. 18.

Gislerud, O. 1982. Storing and drying of energy chips for small-scale chip heating. Norwegian For. Res. Inst., As-NLH.

Harker, A.P., A. Sandels and J. Burley. 1982. Calorific values for wood and bark - a bibliography for fuelwood. Tropical Products Institute, London.

Howard, E.T. 1973. Heat of combustion of various southern pine materials. Wood Sci. 5(3), 194-197. (quoted by Sastry and Anderson, 1980).

Isachsen, O. 1982. Systems of trade, handling and distribution of wood fuels in Norway. Poster Session, Bioenergy Projects in Norway, October, 1982.

Karcher, W. 1982. Standardization aspects in PAH/POM analysis. Lecture at NATO Advanced Research Workshop on Polycyclic Organic Matter from Exhaust Gases. Leige, August 30 - September 2, 1982.

Karcher, W., R.J. Fordham, A. Nelen, R. Depaus, J. Dubois and Ph. Glaude. 1981. Molecular spectra of polycyclic aromatic hydrocarbons. IECS Workshop on Polynuclear Aromatic Hydrocarbons, Paris, October, 1981.

Karchesy, J. and P. Koch. 1979. Energy production from hardwoods growing on southern pine sites. USDA For. Serv., Gen. Tech. Rep. SO-24. U.S. Govt. Printing Office, Washington, D.C.

Koch, P. 1972. Utilization of the southern pines. U.S. Govt. Printing Office, Washington, D.C. Vol. 1.

Marsinko, A.P.C. and T.C. Wooten. 1982. Firewood, pickup trucks, cords and other units of measurement. Clemson University, Dept. Forestry, Forestry Bulletin.

Martin, G. and W. Francis. 1954. Industrial and manufacturing chemistry, Part II. p. 1-68, 543, 553.

Neenan, M. 1982. Short-rotation forestry as a source of energy and chemical feedstock. Proc. 2nd EEC Conference on Energy from Biomass, Berlin 1982. In press.

Neenan, M. and K. Steinbeck. 1979. Calorific values for young sprouts of nine hardwood species. For. Sci. 25, pp. 455-461.

Nilsson, L.O. 1982. Determination of current energy forest growth and biomass production. Sveriges Lantbruksuniversitat, Upsala, Energy Forestry Project, Technical Rep. No. 22.

Olkinuoura, P. 1982. Systems and equipment for efficient use of wood, straw and peat as fuel in agriculture. FAO/ECE Working Party on Mechanization of Agriculture. 28th Session, October, 1982.

Paavilainen, E. and A. Perm. 1981. Biomass yields and management of natural coppice stands. IEA/FE PG'B' Report No. NE 1981:19.

Ramdahl, T., I. Alfheim and A. Bjorseth. 1981. Sources and emission factors of polycyclic aromatic hydrocarbons. OECD Workshop on Polycyclic Aromatic Hydrocarbons, Paris, October, 1981.

Ramdahl, T., I. Alfheim, S. Rustad and T. Olsen. 1982. Chemical and biological characterization and emissions from small residential stoves burning wood and charcoal. Chemosphere, Vol. 11, No. 6, pp. 601-611.

Sastry, C.B.R. and H.W. Anderson. 1980. Clone variation in the gross heat of combustion of juvenile Populus hybrids. Can. J. For. Res. 10, No. 3.

Sennerby, L. 1979. Wood properties of Salix caprea and Salix pentandra. The Swedish Univ. of Agr. Sci., Dept. For., Products Report No. 197.

Steenackers, V. and J. van Slycken. 1980. Activity Report 1980. Govt. Poplar Research Station, Geraardsbergen, Belgium. Ministry of Agriculture, Ghent., Belgium. p. 6-7.

Stevens, M. 1982. Density variation and lignification in some poplar hybrids. Planning Group B, 9th Meeting (PG'B'9), Belgium, April, 1982.

Tillinan, D.A. 1978. Wood as an energy source. Academic Press, New York.

Zsuffa, L. and D. Morgan. 1982. The use of Populus and Salix biomass for energy. A survey of International Poplar Commission countries. International Poplar Commission Meeting, Casale Montgerrato, Italy, September, 1982.

Appendix 1: Results of a questionnaire concerning the use of wood as fuel in different countries

	Aus.	Can.	E.	Dk.	Fin.	Ger.	Ire.	N.Z.	Nor.	Sw.	U.S.	U.K.
USE OF WOOD a) domestic fuel b) in small industries e.g. sawmills c) in power stations	a,b,c	a,b		a,b,d	a,b,c	a,b,c	a (c)	a,b,c	a,b,d*	a,b,c	a,b,c	a,b
SPECIES	Spruce	Hard & soft woods	Wood little used	Birch etc.	Birch etc.	Many	Spruce etc.	Soft woods	Birch etc.	Birch etc.	Hard woods etc.	Hard & soft woods
RELATIVE IMPORTANCE (in order): a) forest thinnings b) wood waste from industry c) coppice wood	b,c,a, d	b,d,a		b,a	a,b,d	b,c,a, d	b,a	b,a,d	c,a,d	b,a,e** c,d	b,d,a c	b,a,c, d
TYPE OF DOMESTIC BURNER: a) open fires b) grates with/without boilers c) stoves d) boilers for central heating	c,d,b, a	c,a		c,d,b, a	d,c,b	c,d	a,b,c	b,c	c,a,d	d	c,a,d	a,b,c d

Appendix 1 Contd.,

	Aus.	Can.	B.	Dk.	Fin.	Ger.	Ire.	N.Z.	Nor.	Sw.	U.S.	U.K.
DIMENSIONS OF WOOD FOR DOMESTIC HEATING	-	16"etc		30-50 cm 10-30	6cm dia	15cm dia	45cm long	30x15 cm	Vari-able	5-10 cm dia	Vari-able	Logs or chips
SIZE OF POWER PLANTS:												
a) 0-5 megawatts												
b) 5-40 "	50	5-40		0	10-40	0-2	5-60	5	0	0	5-100	0
c) 40-100 "												
d) Over 100 "												
METHOD OF PROCUREMENT:												
a) from within the industry												
b) delivered by contractor	a,b	a,b		a	b,a,c	a,b	b	a,b	a	a,b	a,b	a,b
c) otherwise												
PURCHASING SPECIFICATION:												
a) cubic metres solid												
b) cubic metres chipped	a,c	V.cords		a,b	a,b	a,b,c	c	c	a,d***	b,c	c	a,c
c) weight												
PERIOD OF STORAGE:												
a) 0-3 weeks												
b) 3-6 weeks	d	c		a,d	b(d)	d	b	a,b,c, d	d	d	c,d	Vari-able
c) 6-12 weeks												
d) over 12 weeks												

Appendix 1 Contd.,

	Aus.	Can.	B.	Dk.	Fin.	Ger.	Ire.	N.Z.	Nor.	Sw.	U.S.	U.K.
GOVT. REGULATIONS OR STANDARDS IN EXISTENCE: a) dryness b) size of unit	0	0		0	0	0	0	0	b	****	+	0
EXISTENCE OF INHIBITORY REGULATIONS (+ - Govt.):	-	Insur-ance		0	0	+	0	+	Tax	+	+	+
OBJECTIVE OF REGULATIONS: a) appearance of the countryside b) emissions from flues and chimneys c) danger of chimney fires d) wood smoke and health of workers	b,d	b		-	-	-	-	a,b,c, d	-	b,c,d	b,c	b

* Norway has added a new category "d" which is the use of wood in pulp and paper mills
** Sweden has added a new category
*** Norway added cubic metres stacked
**** Pending

POOR

QUALITY

ORIGINAL